

A Search for the Fourth SM Family Quarks through Anomalous Decays

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Abstract

The existence of fourth family follows from the basics of the Standard Model. Because of the high masses of the fourth family quarks, their anomalous decays could be dominant, if certain criteria are met. This will drastically change the search strategy at hadron colliders. We show that the fourth SM family down quarks with masses up to 400 – 450 GeV can be observed (or excluded) via anomalous decays by Tevatron before the LHC.

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Recently, the search for the fourth SM family has drawn attention of both theoretical and experimental HEP community [1–3]. The existence of the fourth SM family is the outcome of the flavor democracy hypothesis and the actual spectrum of the third family fermion masses [4–6] (see, also review [7] and ref’s therein). Twenty years’ ongoing discussions on “precision data vs fourth SM family” have been concluded in favor of the fourth SM family (see [8, 9] and ref’s therein). Today, the mass and the mixing patterns of quarks and leptons are the most mysterious aspects of particle physics. Within the SM all these masses and mixings are put by hand and constitute the basic source of parameter inflation. The discovery of the fourth SM family could provide some systematics for SM fermion masses and mixings, which seems chaotic in the three family case.

Let us remind that flavour physics met a lot of surprises. The first example was discovery of μ -meson (We were looking for π -meson predicted by Yukawa but discovered the “heavy electron”). The next example was represented by strange particles (later we understood that they contains strange quarks). The story was followed by τ -lepton, c- and b-quarks discovered in 1970’s. Actually, c-quark was foreseen by GIM mechanism and quark-lepton symmetry and its mass was estimated in the few GeV region, whereas the discovery of τ -lepton and b-quark was completely surprising for physicists. According to the Standard Model they are the members of the third fermion family, which was completed by the discovery of t-quark in 1995 at Tevatron. Actually, we need at least three fermion families in order to handle CP-violation within the SM [10]. CP violation is necessary for the explanation of Barion Asymmetry of the Universe (BAU). Unfortunately, SM with three fermion families does not provide actual magnitude for BAU. Fortunately, the fourth SM family could provide additional factor of order of 10^{10} and, therefore, solve the problem [11].

The existence of the fourth SM family could affect the Tevatron physics search program in two ways. First, it leads to essential enhancement of the Higgs production via gluon fusion (see, [12, 13] and ref’s therein). As a result, while in the case of three SM families (SM3) Tevatron data on $gg \rightarrow H \rightarrow WW \rightarrow ll' P_T^{mis}$ process excludes $162 \text{ GeV} < M_H < 166 \text{ GeV}$ [14] at 95% CL, the excluded region becomes $131 \text{ GeV} < M_H < 204 \text{ GeV}$ [15], if the Nature prefers four SM families case. Second, if the masses of the fourth family quarks are not so large, they could be directly observed by Tevatron.

Up to now, all searches for the fourth family quarks have been done by assuming that SM decay modes are dominant. Current lower limits on the fourth SM family quark masses

from direct searches at the Tevatron are:

a) $M_{d_4} > 338$ GeV at 95% CL coming from the search for new bottom-like quark pair decays in same-charged lepton events with an integrated luminosity of 2.7 fb^{-1} [16],

b) $M_{u_4} > 256$ GeV at 95% CL coming from the search for heavy top-like quarks, using lepton plus jets events with an integrated luminosity 0.76 fb^{-1} [17].

The heaviness of the t-quark has induced searches for its anomalous interactions [18–22]. For the same reason – new quarks are heavier than t-quark – in the search strategy the anomalous interactions for the fourth SM family quarks should be taken into account. These interactions may manifest themselves both in the production and decays of new quarks. If the anomalous decay modes of the fourth family quarks are dominant, lower limits on their masses given above are not valid and the search strategy should be changed drastically.

In this letter, we consider pair production of the fourth SM family down-type quarks with subsequent anomalous decays into photon+jet and jet+jet channels. More general consideration, including other manifestations, will be presented in the following publication [23].

The effective Lagrangian for anomalous magnetic type interactions of the fourth family quarks is given as [24–26]:

$$L = \sum_{q_i} \frac{\kappa_\gamma^{q_i}}{\Lambda} e_q g_e \bar{q}_4 \sigma_{\mu\nu} q_i F^{\mu\nu} + \sum_{q_i} \frac{\kappa_Z^{q_i}}{2\Lambda} g_Z \bar{q}_4 \sigma_{\mu\nu} q_i Z^{\mu\nu} + \sum_{q_i} \frac{\kappa_g^{q_i}}{\Lambda} g_s \bar{q}_4 \sigma_{\mu\nu} T^a q_i G_a^{\mu\nu} + H.c. \quad (1)$$

where $F^{\mu\nu}$, $Z^{\mu\nu}$ and $G^{\mu\nu}$ are the field strength tensors of the gauge bosons, $\sigma_{\mu\nu}$ is the anti-symmetric tensor, T^a are Gell-Mann matrices, e_q is electric charge of quark, g_e , g_Z and g_s are electromagnetic, neutral weak and strong coupling constants, respectively. $g_Z = g_e / \cos\theta_W \sin\theta_W$ where θ_W is the Weinberg angle. κ_γ , κ_Z and κ_g are the strength of anomalous couplings with photon, Z boson and gluon, respectively. Λ is the cutoff scale for new physics. This type of gauge and Lorentz invariant effective Lagrangian have been proposed in the framework of composite models for interactions of excited fermions with ordinary fermions and gauge bosons [25, 26].

For numerical calculations we implement the Lagrangian (1), as well as fourth family SM Lagrangian into the CalcHEP package [27]. The partial decay widths of d_4 for SM ($d_4 \rightarrow W^- q$ where $q = u, c, t$) and anomalous ($d_4 \rightarrow \gamma q$, $d_4 \rightarrow Z q$, $d_4 \rightarrow g q$ where $q = d, s$,

b) modes are given below:

$$\Gamma(d_4 \rightarrow W^- q) = \frac{|V_{qd_4}|^2 \alpha_e M_{d_4}^3}{16 M_W^2 \sin^2 \theta_W} \chi_W \sqrt{\chi_0} \quad (2)$$

where $\chi_W = (1 + x_q^4 + x_q^2 x_W^2 - 2x_q^2 - 2x_W^4 + x_W^2)$, $\chi_0 = (1 + x_W^4 + x_q^4 - 2x_W^2 - 2x_q^2 - 2x_W^2 x_q^2)$, $x_q = (M_q/M_{d_4})$ and $x_W = (M_W/M_{d_4})$,

$$\Gamma(d_4 \rightarrow Z q) = \frac{\alpha_e M_{d_4}^3}{16 \cos^2 \theta_W \sin^2 \theta_W} \left(\frac{\kappa_Z^q}{\Lambda}\right)^2 \chi_Z \sqrt{\chi_1} \quad (3)$$

where $\chi_Z = (2 - x_Z^4 - x_Z^2 - 4x_q^2 - x_q^2 x_Z^2 - 6x_q x_Z^2 + 2x_q^4)$, $\chi_1 = (1 + x_Z^4 + x_q^2 - 2x_Z^2 - 2x_q^2 - 2x_Z^2 x_q^2)$ and $x_Z = (M_Z/M_{d_4})$

$$\Gamma(d_4 \rightarrow g q) = \frac{2\alpha_s M_{d_4}^3}{3} \left(\frac{\kappa_g^q}{\Lambda}\right)^2 \chi_2 \quad (4)$$

where $\chi_2 = (1 - 3x_q^2 + 3x_q^4 - x_q^6)$,

$$\Gamma(d_4 \rightarrow \gamma q) = \frac{\alpha_e M_{d_4}^3 Q_q^2}{2} \left(\frac{\kappa_\gamma^q}{\Lambda}\right)^2 \chi_2 \quad (5)$$

One can wonder what is the criteria for the dominance of anomalous decay modes over SM ones. It is seen from Eq. (2)-(5) that the anomalous decay modes of the fourth SM family quarks are dominant, i.e. $\Gamma(d_4 \rightarrow g q) + \Gamma(d_4 \rightarrow Z q) + \Gamma(d_4 \rightarrow \gamma q) > \Gamma(d_4 \rightarrow W^- q)$, if the relation $(\kappa/\Lambda) \gtrsim 1.2(V_{ud_4}^2 + V_{cd_4}^2 + V_{td_4}^2)^{1/2} \text{ TeV}^{-1}$ is satisfied (hereafter $\kappa_Z^q = \kappa_g^q = \kappa_\gamma^q = \kappa$ is assumed). The experimental upper bounds for the fourth family quark CKM matrix elements are $|V_{u_4 d}| \leq 0.063$, $|V_{u_4 s}| \leq 0.46$, $|V_{u_4 b}| \leq 0.47$, $|V_{ud_4}| \leq 0.044$, $|V_{cd_4}| \leq 0.46$, $|V_{td_4}| \leq 0.47$ [28]. On the other hand, the predicted values of these matrix elements are expected to be rather small in the framework of flavor democracy hypothesis. For example, the mass matrix parametrization proposed in [29], which gives correct predictions for CKM and MNS mixing matrix elements through use of SM fermion mass values as input, predicts $|V_{u_4 d}| = 0.0005$, $|V_{u_4 s}| = 0.0011$, $|V_{u_4 b}| = 0.0014$, $|V_{ud_4}| = 0.0002$, $|V_{cd_4}| = 0.0012$, $|V_{td_4}| = 0.0014$. In this case, the anomalous decay modes are dominant, if $(\kappa/\Lambda) > 0.0022 \text{ TeV}^{-1}$. The latter corresponds to upper limit 500 TeV for new physics scale Λ , assuming $\kappa = O(1)$.

The cross-section for the $d_4 \bar{d}_4$ pair production at the Tevatron is shown in Fig. 1. We have used CalcHEP [27] with CTEQ6L [30] parton distribution functions for numerical

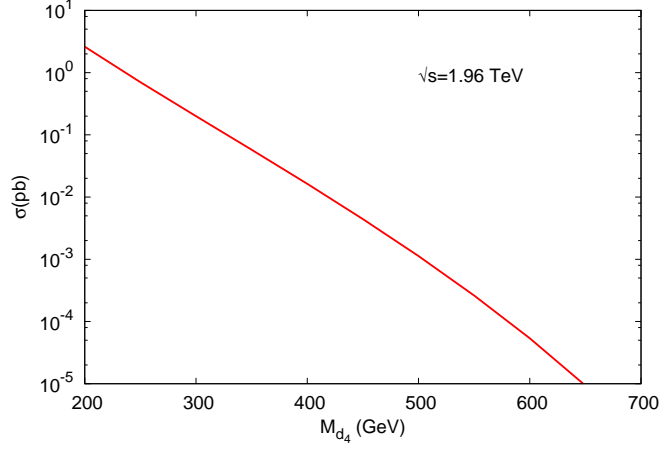


Figure 1: Cross section for $d_4\bar{d}_4$ pair production at the Tevatron.

M_{d_4}	200 GeV		300 GeV		400 GeV	
cuts	σ_S , fb	σ_B , fb	σ_S , fb	σ_B , fb	σ_S , fb	σ_B , fb
$p_T > 20\text{GeV}$	39.2	5.4×10^5	2.92	5.4×10^5	0.23	5.4×10^5
$p_T > 50\text{GeV}$	24.5	2.7×10^3	2.40	2.7×10^3	0.21	2.7×10^3
all cuts	21.8	3.63	2.27	0.091	0.20	0.006

Table I: Signal and background cross sections values for various cuts. All cuts include $p_T > 50$ GeV, $|\eta| < 2$, $|M_{inv}(\gamma j) - M_{d_4}| < 20$ GeV, $|M_{inv}(jj) - M_{d_4}| < 20$ GeV.

calculations. One can see that if M_{d_4} is about 400 GeV the Tevatron with $L_{int} = 10 \text{ fb}^{-1}$ will yield more than hundred $d_4\bar{d}_4$ pairs.

We propose $p\bar{p} \rightarrow d_4\bar{d}_4 \rightarrow \gamma q g \bar{q}$ (where $q = d, s, b$) process to analyze the Tevatron search potential to discover d_4 quark via anomalous decays. In detector this process is seen as $\gamma + 3j$ events. We use CalcHEP [27] and MADGRAPH [31] packages with CTEQ6L [30] parton distribution functions for the calculation of the signal and background processes, respectively. In order to extract the d_4 signal and to suppress the background, following cuts are applied: $p_T > 50$ GeV and $|\eta| < 2$ for all final state partons and photon, as well as invariant mass within ± 20 GeV around d_4 mass. The effects of these cuts can be seen from Table I.

Statistical significance has been calculated by using following formula [32]:

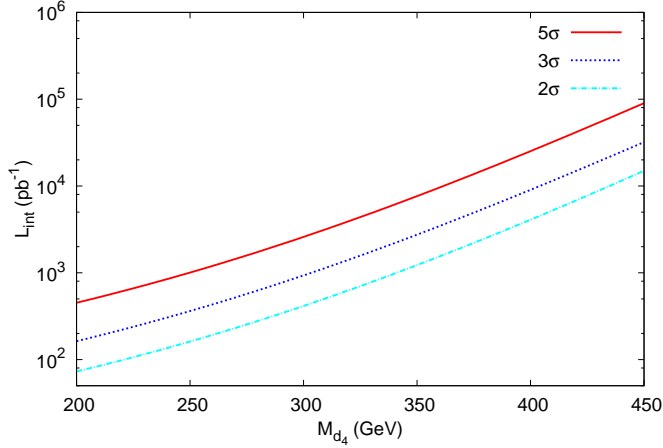


Figure 2: The necessary integrated luminosity for the observation of d_4 quark at the Tevatron

L_{int}, fb^{-1}	5	10	20
2 σ exclusion	390 GeV	430 GeV	460 GeV
3 σ observation	370 GeV	410 GeV	440 GeV
5 σ discovery	340 GeV	360 GeV	390 GeV

Table II: Reachable M_{d_4} mass values for discovery, observation and exclusion at the Tevatron.

$$S = \sqrt{2[(s+b)\ln(1 + \frac{s}{b}) - s]} \quad (6)$$

where s and b represents the numbers of signal and background events, respectively.

In Fig. 2 the necessary integrated luminosities for the observation of d_4 quark at the Tevatron are plotted as a function of d_4 mass. It is seen that the fourth family down quarks with masses below 375 GeV could be excluded at 95% CL with 2.7 fb^{-1} integrated luminosity, if the corresponding analysis of data has been performed (compare with 338 GeV for SM modes dominant case [16]). Discovery, observation and exclusion for the different values of the Tevatron integrated luminosity are given in Table II.

Summary and Outlook. – Keeping in mind the LHC status, the Tevatron has about 2 more years for new physics discovery. The fourth SM family quarks are among the most prominent candidates for beyond the SM3 physics and possible dominance of their anomalous decay modes should not be ignored. If these modes are dominant, the fourth SM family down quarks with masses up to 400-450 GeV can be observed (or excluded) via anomalous decays

by Tevatron before the LHC.

Acknowledgments

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- [1] B. Holdom *et al.*, PMC Phys. **A 3**, 4 (2009).
- [2] Beyond the 3SM, 1st workshop at CERN, <http://indico.cern.ch/conferenceDisplay.py?confId=33285>.
- [3] Beyond the 3SM, 2nd workshop in Taiwan, <http://indico.cern.ch/conferenceDisplay.py?confId=68036>.
- [4] H. Fritzsch, Phys. Lett. B **289**, 92 (1992).
- [5] A. Datta, Pramana **40**, L503 (1993).
- [6] A. Celikel, A. Ciftci and S. Sultansoy, Phys. Lett. B **342**, 257 (1995).
- [7] S. Sultansoy, The Naturalness of the Fourth SM Family, arXiv:0905.2874[hep-ph].
- [8] O. Cobanoglu *et al.*, OPUCEM: A Library with Error Checking Mechanism for Computing Oblique Parameters, arXiv:1005.2784 [hep-ex].
- [9] O. Eberhardt, A. Lenz and J. Rohrwild, Less space for a new family of fermions, arXiv:1005.3505 [hep-ph].
- [10] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
- [11] W.-S. Hou, Chin. J. Phys. **47**, 134 (2009).
- [12] E. Arik *et al.*, Phys. Rev. D **66**, 033003 (2002); E. Arik *et al.*, Acta Phys. Polon. B **37**, 2839 (2006).
- [13] N.Becerici Schmidt *et al.*, Eur. Phys. J. C **66**, 119 (2010).
- [14] T. Aaltonen *et al.* (CDF and D0 Collaborations), Phys. Rev. Lett. **104**, 061802 (2010).
- [15] T. Aaltonen *et al.* (CDF and D0 Collaborations), Combined Tevatron upper limit on $gg \rightarrow H \rightarrow W^+W^-$ and constraints on the Higgs boson mass in fourth-generation fermion models, arXiv:1005.3216 [hep-ex];
- [16] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett **104**, 091801 (2010).
- [17] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett **100**, 161803 (2008).
- [18] H. Fritzsch and D. Holmanspotter, Phys. Lett. B **457**, 186 (1999).
- [19] F. Abe et al. (CDF Collaboration), Phys. Rev. Lett **80**, 2525 (1998).

- [20] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett **99**, 191802 (2007).
- [21] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett **101**, 192002 (2008).
- [22] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett **102**, 151801 (2009).
- [23] M. Sahin, S. Sultansoy and S. Turkoz, A Search for the Fourth SM Family: Tevatron still has a Chance (in preparation).
- [24] E. Arik, O. Cakir and S. Sultansoy, Eur. Phys. J. C **39**, 499 (2005).
- [25] N. Cabibbo, L. Maiani and Y. Srivastava, Phys. Lett. B **139**, 459 (1984).
- [26] K. Hagiwara, S. Komamiya and D. Zeppenfeld, Z. Phys. C - Particles and Fields **29**, 115 (1985).
- [27] A. Pukhov *et al.*, hep-ph/9908288.
- [28] V.E. Ozcan, S. Sultansoy and G. Unel, Eur. Phys. J. C **57**, 621 (2008).
- [29] A.K. Ciftci, R. Ciftci and S. Sultansoy, Phys. Rev. D **72**, 053006 (2005).
- [30] J. Pumplin *et al.*, JHEP **0207**, 12 (2002); D. Stump *et al.*, JHEP **0310**, 046 (2003).
- [31] F. Maltoni and T. Stelzer, JHEP **0302**, 027 (2003).
- [32] G.L. Bayatian *et al.* (CMS Collaboration), J. Phys. G **34**, 995 (2007).